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Extreme Ultraviolet Lithography for 0.1 μm Devices[1]

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Abstract

Extreme Ultraviolet Lithography (EUVL) has emerged as one of the leading successors to optics for 0.1 μm IC fabrication. Its strongest attribute is the potential to scale to much finer resolution at high throughput. As such, this technique could meet the lithography needs for Si ULSI down to fundamental device limits. In the United States, Lawrence Livermore, Sandia, and Lawrence Berkeley Laboratories are participating in an industry funded research effort to evolve EUV technology and build a prototype camera for lithographic exposure. More recently, both Europe and Japan have initiated government/ industry sponsored programs in EUVL development. This talk will focus on our program successes to date, and highlight some of the challenges that still lie ahead.

Introduction

Lithography is generally viewed as the enabling technology for the progressive reduction in design rules for each semiconductor generation. For the last several decades, optical projection has maintained its dominance in high-volume manufacturing and it is now widely accepted that improvements in optics and mask technologies will allow it to extend towards 100 nm minimum feature size. Extensions of optical lithography have been made possible by a continuous reduction in the exposure wavelength λ and simultaneous increase in numerical aperture NA. The question of how long this trend can continue, using refractive/catadioptric lens designs, is one that continues to be actively debated. The National Technology Roadmap for Semiconductors (NTRS)[1] shows optical lithography as the desired mainstream approach down to at least 100 nm. At these feature sizes, the optical approaches will require robust, vacuum UV (VUV), transparent/reflective materials and coatings, and complex proximity-corrected phase shifted masks, which could be prohibitively expensive. Below 100 nm, new approaches have been identified. At least four "Next-Generation Lithographies" (NGL) have demonstrated feasibility and are in various stages of development. These are EUVL (4x reduction with 13.4 nm radiation using reflective optics and mask), SCALPEL[2] (4x reduction e-beam and scattering membrane mask), x-ray[3] (one-to-one using hard x-rays with membrane mask), and ion beam (4x reduction and stencil mask). Within the U.S., EUVL is being developed under the auspices of an industry funded consortium, the LLC, which is supporting the combined activities of Lawrence Livermore National Laboratory, Sandia National Laboratory and Lawrence Berkeley Laboratory.

Why EUVL? The reasons can be easily understood by considering the two most fundamental characteristics of an imaging system, the resolution (RES) and depth of focus (DOF), expressed as

$$\mathrm{RES} = \frac{k_1\lambda}{\mathrm{NA}} \quad \text{and} \quad \mathrm{DOF} = \frac{k_2\lambda}{\mathrm{NA}^2}$$

The penalty for decreasing λ and increasing NA for improved resolution is a smaller DOF. The parameters k_1 and k_2 are generally set for a manufacturing process based on the desired line width control within the allocated process window. Other factors such as the contrast of the resist and the characteristics of the etch process also play a role. The "comfort zone" in an advanced manufacturing line corresponds to $k_1 = 0.5$ and DOF ≈ 0.5 μm today. These values will shrink through the use of reticle enhancement techniques such as optical proximity correction and phase shifted masks, modified illumination schemes, thinner, higher contrast resists, improved surface planarization, better etch process control, and stitch-and-scan exposure architecture, until optics are no longer cost competitive with an NGL.

EUVL mitigates these problems by decreasing both the λ and NA (see Figure 1) without relying on additional expensive avenues for wavefront control. A 13.4 nm, 0.25 NA design can theoretically print 30 nm features!

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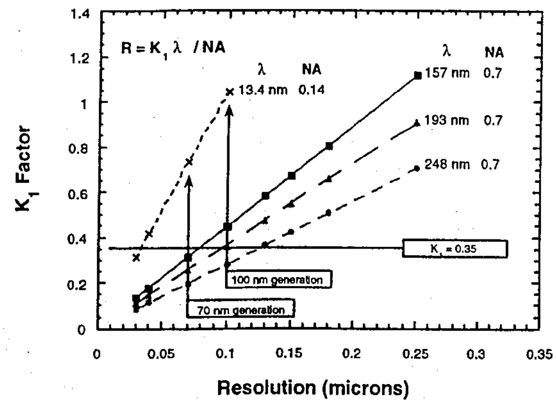

Figure 1. k_1 required to meet resolution targets for each of the optical technologies assuming an NA = 0.7 for the DUV/VUV approaches and NA = 0.14 for EUV

EUV Technology

While the basic optical design tools for EUV imaging are the same as those used today for optical projection lithography, EUV technology is far removed from current UV requirements primarily because materials behave very different in EUV than in the visible and UV.

a. Multilayer Reflectives

Foremost amongst the differences is the fact that EUV radiation is strongly absorbed in virtually all materials including gases. Thus EUVL imaging systems are entirely reflective. To achieve reasonable reflectivity near normal incidence, surfaces are coated with multilayer (ML) thin films of dissimilar optical constants which act as distributed Bragg reflectors at a period of $\lambda/2$. The best of these function between 11 and 14 nm, where close to theoretical reflectivities are being demonstrated (Figure 2)[4].

Since a typical EUVL camera is comprised of at least 4 mirrors, and light falls on each over different angular ranges, the periods of the MLs need to vary and may even change over each mirror to maintain high throughput and image fidelity.

b. EUV Exposure Systems

To ensure diffraction-limited imaging performance, the EUV camera is comprised of mirrors with aspheric surfaces, with an unprecedented degree of perfection in both surface figure and finish (Figure 3). The figure specification is set by the constraint that the total wavefront of the assembled camera cannot exceed 0.07 waves rms for diffraction-limited imaging. The mid-spatial frequency specification sets the allowable flare in the system; and the high-spatial frequency roughness defines mirror reflectivity and therefore camera throughput. The EUV program is driving the state of the art in each of these requirements for optics fabrication. Working with vendors, recent measurements have demonstrated 0.4 nm figure, 0.15 nm mid- and 0.1 nm high-spatial frequency roughness on aspheres. A schematic of a 4-mirror, 4x reduction prototype imaging system, currently under development, is also shown in Figure 3[5]. It is designed for use with Mo:Si MLs at 13.4 nm and has an NA = 0.1. The camera is intended for use in a step and scan mode and should exhibit better than 100 nm resolution over a 15 mm x 26 mm ring-shaped field. This tool also includes a laser produced plasma EUV source, condensing optics, a multilayer coated re-

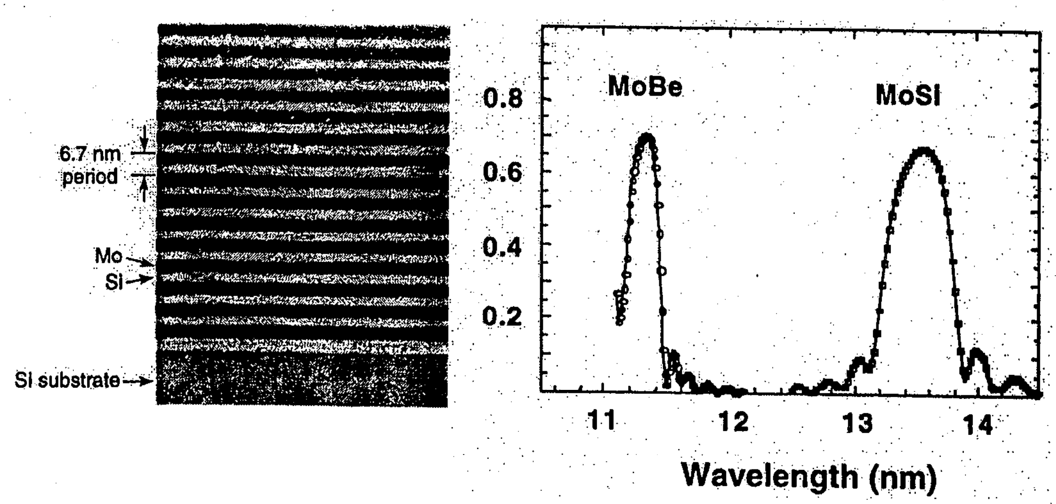

Figure 2. Transmission electron micrograph (TEM) of a MoSi multilayer coating used at 13.4 nm is shown on the left. On the right are typical reflectivity curves for MoSi and MoBe.

flective mask, precision scanning stages, and a vacuum enclosure.

c. Metrology

Success in optics fabrication and camera alignment could not have been possible without two significant innovations in metrology: first, the ability to measure surface figure with a point-diffraction interferometer to an absolute accuracy of better than 0.25 nm rms;[6] and second, the development of an EUV interferometer with an rms accuracy of 0.003 waves at EUV wavelengths.[7] As a testimonial to these metrology capabilities, Figure 4 illustrates the wavefront quality of an assembled 10x EUV imaging camera measured by the two different techniques.

Figure	0.25 nm rms
Mid-spatial frequency	0.20 nm rms
High-spatial frequency	0.10 nm rms

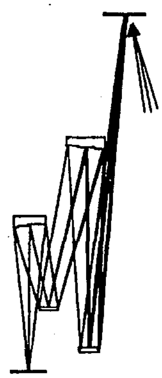

Figure 3. At the right of this figure is shown a 4-mirror EUVL imaging system composed of a reflective mask, a set of projection optics, and a resist-coated wafer. At top left are fabrication specifications for the projection optics substrates.

d. Resists and Imaging Results

Because of the strong absorption of EUV radiation in all materials, resist thicknesses of 100 nm or below are required. Single, bi-layer and tri-layer schemes are in development. A photosensitivity of 10 mJ/cm^2 or better is necessary for adequate system throughput.

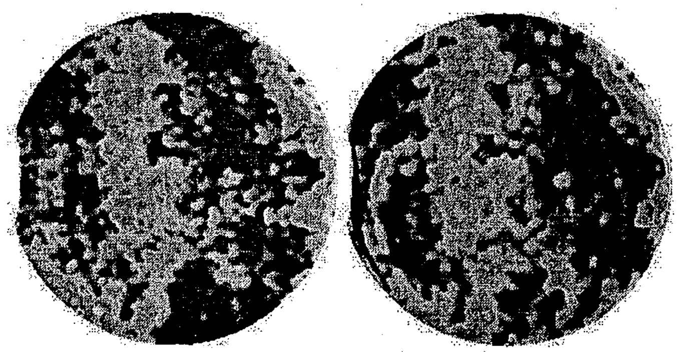

Figure 4. Side by side comparison of interferograms of an assembled 10x EUV camera. The one on the left was taken with EUV light while the one on the right was taken with visible light. The rms values differ by only approximately 0.02 nm. The rms wavefront error for each is approximately 0.8 nm.

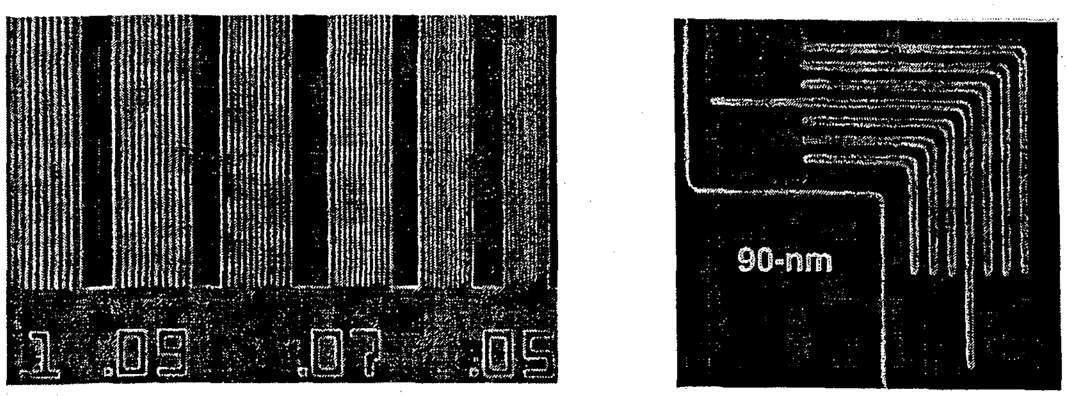

Figure 5. Patterns printed in 80 nm of resist using a 10x reduction EUV laboratory tool. The features on the right show excellent isolated and dense 90-nm features, while the electron micrograph on the left shows a variety of features with critical dimensions from 100 nm to 50 nm.

Summary

The EUV LLC, working together with the National Laboratories is in the process of assembling a prototype scanning exposure system for wafer exposure by 2001. Supplier infrastructure development is ongoing in parallel.

Impressive successes in EUV component technologies over the past several years have positioned this approach as the most likely successor to "conventional" optics. Moreover, by modifying the camera design, EUVL could meet the lithographic challenge of defining the minimum geometry Si-transistor deemed possible, at a respectable throughput.

However, a transition from optical lithography to EUVL in an IC manufacturing line will only occur when the cost per wafer level exposure with EUVL is lower than the incumbent approach. Perhaps the two predominant cost centers in EUVL are the mask technology and the EUV source. Since there are no straightforward means of repairing ML defects, ML-coated blanks must exhibit defect densities of about $0.01/cm^2$ at 60 nm size for adequate mask-yield. This challenges thin-film deposition, defect inspection, and mask fabrication and repair processes. Nevertheless, if the past progress is any indication of the future, it is our belief that the international research teams in EUVL will surmount the technical hurdles still remaining, and deliver *the* post-optical patterning capability for 0.1 μm integrated circuits.

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